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A STUDY OF TURBULENT FLOWS ABOUT OSCILLATING AIRFOILS.(U)

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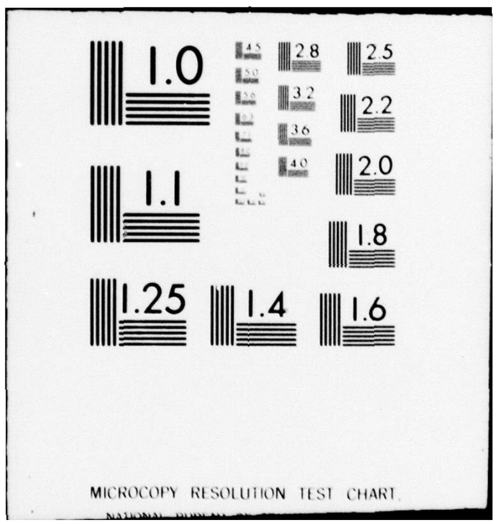
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A two-equation differential model of turbulence has been studied in detail and used in conjunction with a integro-differential approach for the numerical solution of separated flow problems. A number of turbulent flow problem have been solved numerically and the results obtained have been compared with available experimental data. The most significant result of this research is that a versatile and highly efficient approach has been made available for numerically solving complex turbulent flow problems. The cornerstone of this research project is the integro-differential approach developed by the principal investigator and his co-workers.

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A STUDY OF TURBULENT FLOWS

ABOUT OSCILLATING AIRFOILS

Final Report
prepared by
J. C. Wu

September 18, 1978

for the
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Georgia Institute of Technology
School of Aerospace Engineering

STATEMENT OF PROBLEM

The major objectives of this research are to develop a general computational capability for the prediction of time-dependent turbulent flows which may involve appreciable flow separation and strong viscous-inviscid interaction and to obtain numerical results that contribute to the understanding of the problem of dynamic stall. Towards these objectives, a two-equation differential model of turbulence has been studied in detail and used in conjunction with a integro-differential approach for the numerical solution of separated flow problems. A number of turbulent flow problem have been solved numerically and the results obtained have been compared with available experimental data.

IMPORTANT RESULTS

The most significant result of this research is that a versatile and highly efficient approach has been made available for numerically solving complex turbulent flow problems. The cornerstone of this research project is the integro-differential approach developed by the principal investigator and his co-workers.

The mathematical foundation of this approach was established prior to the initiation of this project. A number of important attributes of this approach was pointed out. The approach, however, was only applied to study several low Reynolds number flows involving simple flow geometries. Under the present project, the approach has been further developed and used to study highly complex separated flow problems at high Reynolds numbers. The important attributes of the approach has been conclusively demonstrated. User-oriented packages of computer codes have been prepared for various types of separated flows.

A most important attribute of the integro-differential approach is its ability to confine the solution region to the vortical region of the flow. For problems where the flow Reynolds number is not small, the vortical region

occupies only a very small part of the total fluid domain and possesses a small length scale. The remainder of the flow is irrotational and possesses a much larger length scale. A suitable grid system must have grid points closely spaced in the vortical region in order to have sufficient solution resolution and accuracy. With conventional numerical methods, the irrotational and vortical regions are treated together. It is difficult to design a grid system that possesses closely spaced grid points in the vortical region and yet does not contain an exceedingly large number of grid points to represent the entire flow. This difficulty is one of the major motivations for the development coordinate-transformation and finite-element techniques in recent years. With these techniques, it is possible to design an "expanding" grid system,the spacing between grid points increasing with the distance from a solid boundary. In this manner, the number of grid points in the irrotational region, which is often far from the solid boundary, is minimized. These techniques alleviate, but do not eliminate, the difficulty of having to deal with two vastly different length scales concurrently. In particular, with increasing Reynolds number, the length scale in the vortical region decreases so that this difficulty becomes more acute. The ability of the integro-differential approach to confine the solution field to the vortical region obviously removes this difficulty. This unique ability has been implemented under the present project. The development of this approach has been brought to a reasonable stage of sophistication and completion so that various two-dimensional flow problems can be solved routinely now using widely accessible computers. For example, several problems involving unsteady laminar flows past airfoils have been studied numerically under separate projects. The unsteady flows included those associated with an airfoil in oscillatory pitching motion and those associated with an impulsively started airfoil. Several airfoil configurations have been studied, including many high angle-of-attack cases.

The details of these numerical studies are described in recent articles listed at the end of this report (Articles 10, 17, 19). These details are not repeated here. Representative computing requirements are stated here, however, to indicate the present state of development of the integro-differential approach. Typically, for a unsteady laminar flow past an airfoil, less than 10 minutes of CDC-6600 CPU time is required to advance the numerical solution by one dimensionless unit of physical time, i.e., the time inteval during which the airfoil advances by one chord length relative to the freestream. Based on the experience acquired under this project, it is concluded that most two-dimensional laminar flow problems now can be solved routinely and economically using the integro-differential approach. In fact, for these problems, there is no critical need to further improve the computational efficiency already achieved. Nevertheless, it is worthy of note that several additional refinement has been explored for the purpose of drastic further reductions in computing requirements (Article 22). These refinements are studied mainly with turbulent flows and three-dimensional flows in mind. The most important refinements studied thus far are the separate treatment of the boundary-layer region and the recirculating region (both regions are vortical) and the use of finite Fourier series rather than polynomials in the numerical approximation procedures. It is expected that these refinements when fully implemented will enable the solution of three-dimensional problems using modern digital computers such as the CDC 7600.

In addition to its superior solution efficiency, it has been shown by numerical illustrations and by analysis that the integro-differential approach offers superior solution accuracy (Articles 1, 2, 10, 15, 16, 21), removes certain major difficulties associated with the numerical treatment of boundary conditions (Articles 8 and 11), and is useful under quite general circumstances (Article 9). It is useful for compressible as well as incompressible flows, time-dependent as well as steady flows, three-dimensional as

well as two-dimensional flows, turbulent flows as well as laminar flows. Under the present project, considerable progress has been made in the use of the integro-differential approach for the solution of turbulent flow problems.

It is well known that it is not realistic in the reasonable future to consider the numerical solution of the complete time-dependent Navier-Stokes equations for turbulent flows, including all significant-size turbulent eddies. Such computations would require a formidable amount of computer time and data storage. The development of a reasonably accurate models of turbulence that simulates the flow in important aspects is therefore a more meaningful and rewarding goal. In this regard, it is well known that an accurate and general model of turbulence for separated flows does not exist. For time-dependent flows, the current state of knowledge is especially lacking. Until recently, the lack of highly efficient numerical procedures has severely limited the ability of researchers to test and calibrate various proposed models of turbulence. Because of the necessarily empirical foundation of turbulence modeling, such tests and calibrations must be extensive. The remarkable solution speed and accuracy of the integro-differential approach, implemented under this project, have been utilized in an extensive study of various turbulence models as applied to separated flow problems.

The development of an integro-differential formulation for time-dependent separated flow has been completed under this project. This formulation partitions the problem into its kinetic and kinematic aspects. The kinematic aspect relates the mean vorticity distribution at any instant of time to the mean velocity distribution at that instant. This relation is expressed as an integral representation for the velocity vector and permits an explicit, point by point, computation of the velocity field. The kinetic aspect consists of differential transport equations describing the change of vorticity, turbulence energy, and turbulence energy dissipation through diffusion, ad-

vection, production, and dissipation. A turbulent coefficient of diffusivity is modeled in terms of the turbulence energy and the turbulence energy dissipation. In this manner, the differential two-equation k-ε model of turbulence is incorporated into the integro-differential procedures previously established for the solution of laminar flow problems. The details of this new formulation for turbulent flows are presented in Article 15. For steady flows, a standardized package of computer code was prepared (Articles 13 and 20) for internal flows within arbitrarily prescribed boundaries. This code required only the input of grid point locations and boundary conditions. No additional efforts for handling complex boundary shapes are required. This package is user-oriented and highly efficient. It has been utilized in calibrating various turbulence models in the steady state limit.

Encouraging results have been obtained for a variety of turbulent flow problems, including flows associated with finite plates, cylinders, cavities, and airfoil sections. It has been found that the k-ε two-equation differentials model yields numerical results in good agreement with available experimental data under various circumstances. Some of the results obtained have been published (Articles 15, 16, and 21). Additional results are being prepared for publication.

In addition to the above summarized efforts in computing laminar and turbulent separated flows, a generalized theory for aerodynamic forces and moments have been developed under a separate project (Article 23). This theory offers a great deal of insight into various aerodynamic phenomena and permits various mechanisms of production of lift and drag forces to be identified and interpreted. The theory has been utilized in the study of unsteady aerodynamic forces and moments acting on oscillating airfoils.

PERSONNEL SUPPORTED

James C. Wu, Professor

As the principal investigator of this project, Dr. Wu directed the develop-

ment of the integro-differential approach. He contributed to the theoretical aspect of this study, resolved major difficulties encountered in applying this approach to turbulent flow problems, analyzed and developed several techniques that further improved the solution speed and solution accuracy of this approach. He also developed, under a separate project, a theory for aerodynamic forces and moments that has been utilized in studying the problem of oscillating airfoils.

Magdy M. Wahbah, Post-doctoral Fellow

Dr. Wahbah developed a standardized, user oriented solution procedure for steady internal flows. This procedure has been utilized to test and calibrate various models of turbulence.

A. Sugavanam, Graduate Research Assistant

Mr. Sugavanam prepared the computer programs for the study of various turbulent flow problems. He carried out the detailed computations and analyses, and resolved many difficulties associated with the computation of complex separated flow problems. He is near the completion of his Ph.D. thesis entitled "Numerical Study of Separated Turbulent Flow over Airfoils." This thesis research was carried out while Mr. Sugavanam was supported on this project.

THE INTEGRAL-REPRESENTATION APPROACH

A list of pertinent articles authored by researchers at the Georgia Institute of Technology, with asterisks indicating those in which ARO support is acknowledged.

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